Technology Transition Case Study

Consortium for the Advanced Simulation of Light Water Reactors (CASL)

A DOE Energy Innovation Hub

Introduction: The following is a case study of one example of a relatively new research and development (R&D) funding modality of DOE known as Energy Innovation Hubs. This case study focuses on the Consortium for the Advanced Simulation of Light-water-reactors (CASL) to understand how it was formed, how its work is planned and managed, the governance of the consortium, how intellectual property is managed and what the consortium has produced and its value to the taxpayer who have invested in the project. Perhaps most importantly, this case study provides a number of lessons learned that could be applied to other DOE technology transition programs.

The concept of Energy Innovation Hubs was first brought to the DOE in 2009 and the first ones, including CASL, were established in 2010. Hubs bring together teams of top scientists and engineers from academia, industry, and government to collaborate and overcome critical barriers that limit U.S. energy security. Hubs focus on a single topic, with the objective of rapidly bridging the gaps between basic research, engineering development, and commercialization through a close partnership with industry. To achieve this goal, the Hubs consist of large, highly integrated and collaborative creative teams working to solve priority technology challenges.

CASL Background: In 2010, the DOE Office of Nuclear Energy (NE) issued a Funding Opportunity (FOA) Announcement to solicit a team that would operate its modeling and simulation Energy Innovation Hub. The FOA requested that teams provide their plans to develop a "virtual" version of an operating reactor and how it would address the mission of Hubs to improve U.S. energy security. The proposing teams were also asked for their approach to develop the virtual reactor and the qualifications of the team to execute those plans. After an extensive evaluation that included site visits, CASL was selected to receive $24M per year over a 5 year Phase 1. CASL was also offered the opportunity to apply for a second 5 year phase if they successfully made a significant impact on nuclear energy modeling and simulation.

CASL is an integrated partnership composed of national laboratory, academia, and industry organizations that are leaders in nuclear power research and development. The ten CASL founding partners self-selected one another in late 2009 to form the consortium (as founding members) that formulated the original CASL plan and proposal for Phase 1. CASL partner organizations, which include a wide range nuclear equipment vendors, nuclear power utilities, modeling and simulation software vendors, engineering design organizations and universities, have contributed to the consortium's R&D activities during Phase 1. The consortium's objective is to continue expanding its partnership during Phase 2 to maximize the number of users who have experience with the CASL tools and the ability to access the tools to help analyze problems of interest.

The CASL consists of a core team of founding partner institutions - three industry members, three universities, four national laboratories - and numerous other partner institutions. The founding partner members are:

- Westinghouse Electric Corporation
- Tennessee Valley Authority (TVA)

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- Electric Power Research Institute (EPRI)
- North Carolina State University (NCSU)
- Massachusetts Institute of Technology (MIT)
- University of Michigan (UM)
- Idaho National Laboratory (INL)
- Los Alamos National Laboratory (LANL)
- Oak Ridge National Laboratory (ORNL)
- Sandia National Laboratories (SNL)

The technical focus of CASL is to develop coupled, high fidelity, usable capabilities needed to address LWR operational and safety performance-defining phenomena. The capabilities, embodied within CASL's *Virtual Environment for Reactor Applications* (VERA), are being designed to run efficiently on modern high performance computing platforms and to deliver insights that are based on the integrated effects of all the physical processes that impact reactor operations. CASL's four strategic goals help focus the consortium on completing its mission: 1) develop and effectively apply modern virtual reactor technology; 2) address light water reactor design, operational and safety challenges; 3) engage the nuclear energy community through modeling and simulation; and 4) deploy new partnership and collaboration paradigms.

NE funds CASL as one of its programmatic R&D activities. CASL is led by ORNL and because it is a DOE national lab, NE is able to use the lab's Management and Operations (M&O) contract to directly fund the work. CASL is a consortium arrangement with each member signing an agreement with ORNL. Funding is provided to each CASL partner through subcontracts that are managed by ORNL. The subcontracts are typically established at the beginning of each fiscal year and modified or renewed annually, as appropriate.

At its conclusion, if successful, CASL will have developed, assessed, applied, and broadly deployed a comprehensive collection of M&S technologies capable of addressing many of the current challenges, emerging issues, and evolving opportunities for the nuclear industry. Proactive extensions of VERA to pressurized water reactors (PWRs), boiling water reactors (BWRs), and integral PWRs (iPWRs) will have been realized and deployments to nuclear vendors and utilities as well as the M&S and HPC communities will have taken place. Through these applications and deployments, the CASL technology will demonstrate its capability to improve the cost-effectiveness of nuclear energy generation via design efficiencies, decreased design-iteration cycle time, and enhanced engineering creativity.

Partnership Formation and Governance: Industry role and influence in CASL is inherent by virtue of the way the consortium is structured and managed. First, three of the ten founding partners are industry organizations that represent the three pillars of the community: vendor (design and sell nuclear fuel and reactor designs - Westinghouse); owner/operator (utility - TVA); and R&D arm of the industry (EPRI). The consortium was formed when the founding partners originally self-selected one another, based on a match of CASL strategic goals with partner institutional interest and expertise, to form the partnership that formulated the original CASL execution plan described in the DOE Energy Innovation Hub proposal developed during the Aug 2009 – Mar 2010 time period.

Membership in CASL does not require membership fees, but industry participants are required to share at least 50% of the cost of CASL operations by providing technical experts at reduced labor rates, providing codes or model validation data, and/or providing other tools or services that have commercial value. CASL is not managed and operated with any kind of "formal voting" process for its partner (funded) and affiliate (participating) institutions. Details of CASL's leadership, management, and operations structure and processes are available in the CASL Management Plan, and briefly summarized in later sections of this document. The sole federal agency responsible for CASL's execution and outcomes is the DOE NE.

Resource allocation decisions ultimately reside with the CASL Director, who consults with the Senior Leadership Team (SLT) while arriving at final decisions. An open planning process, driven top-down by CASL strategic goals as supported by L1 milestone schedules and scope, informs the allocation decisions. A stepwise and iterative process is used in arriving at resource allocations on an annual fiscal year (FY) basis.

CASL Organization: CASL uses a hierarchical management structure that is led by a Director who is joined by a Deputy Director and the Chief Scientist to make up the Senior Leadership Team (SLT). The SLT is supported by four Focus Areas (FA) that are organized by the types of physics needed for the modeling and simulation of a LWR. An additional FA is focused on the integration of the products from the physics Focus Areas. Finally, the last FA (for a total of six) is focused on the application of the CASL virtual reactor and the verification, validation, and uncertainty quantification of those tools as they are applied to particular problems. The FA leadership comes from across the CASL organization based primarily on their proven ability to lead a technical team to produce modeling and simulation tools. To keep CASL focused on solving the industry defined Challenge Problems, the Hub assigned a number of Challenge Problem Integrators who have an in-depth understanding of the Challenge Problem and assess how well the CASL developed tools are able to address those problems. CASL is also supported by a number of organizations that provide important program, financial, and contract services.

Major features of CASL's organization are:

- Central, integrated management working predominately from a single location at ORNL: Director with full line authority and accountability for all aspects of CASL; Deputy Director to drive program planning, performance and assessment; Chief Scientist to drive science-based elements; Computational Chief Scientist to oversee and drive cross-cutting computer and computational science assets; and experienced FA Leads and Deputies with responsibility for the core science and engineering elements;
- Strong science, engineering, applications, and design leadership
- A virtual one-roof approach and widespread implementation of state-of-the-art collaboration technology via a Collaboration and Ideation Officer responsible for VOCC Project execution and integration across the core elements;
- Well-informed and timely decision-making and program integration;
- Independent oversight and review via an external Board of Directors advising on annual performance goals, tactical and strategic plans, and performance metrics and Science and Industry Councils for external oversight, review, and advisory functions;
- Integrated project management for scope/schedule/budget planning and tracking and an integrated Operations and Management Support team providing clear leadership for environment, safety, and health; partnerships and IP management; finance and procurement; quality; and security; and
- Robust technology transfer and partnerships with a Technology Deployment and Outreach element to ensure efficient, widespread industrial engagement and coordinated management of intellectual property, ensuring that CASL discoveries and VERA will be translated rapidly to commercial applications.

NE conducts once a year reviews that involve federal employees and teams of independent experts. To date four of these reviews was conducted in accordance with the NE Hub Oversight Plan, where the review charter focused on addressing key questions about CASL's management, execution, and performance. CASL has instituted a formal process to analyze and develop actions for findings and comments resulting from assessments and annual reviews. As needed, responses to the findings are delivered at the next annual review.

CASL has a Board of Directors (BOD) that serves as both an advisory and oversight body for the ORNL Laboratory Director and the CASL Senior Leadership Team (SLT) on issues related to management, performance, strategic direction, and institutional interfaces within CASL. The CASL Director reports to the BOD on all matters related to CASL strategic program plans and decisions. The advice and oversight by the BOD is consistent with commitments made by UT-Battelle, LLC, which is the management contractor for ORNL. The BOD works to ensure the execution of CASL operational and R&D plans provide maximum benefit to key stakeholders such as DOE and the CASL Industry Council. Specifically, the BOD:

- Advises the ORNL Laboratory Director on selected matters of CASL scope, schedule, budget, performance, and strategic direction;
- Advises the CASL SLT on changes to the composition of CASL partners;
- Advises the CASL SLT on strategic direction and annual performance goals; evaluate performance of the SLT on an annual or as-needed basis;
- Helps the CASL SLT in participating in and overseeing the activities of the CASL Science and Industry Councils;
- Reviews and advises on annual project and budget plans and budget allocation changes in excess of $2M to CASL partners on an as–needed basis;
- Supports the CASL and ORNL SLT in managing effective interfaces with key stakeholders, transitional and applied R&D, technology transfer, and commercialization; and
- Assists in and helps foster CASL partner organization interrelationships on an as-needed basis.

The BOD consists of representatives of the executive leadership of CASL founding partner institutions plus a group of up to four at-large internationally recognized leaders in R&D programs or organizations of relevance to CASL. The CASL BOD, which makes decisions by consensus, meets for three full-day meetings annually, with one of those meetings conducted "virtually", namely via video teleconference.

CASL has also implemented an Industry Council (IC) made up of representatives drawn from nuclear power utilities, nuclear technology vendors, engineering services companies and other organizations. The principal purpose of the IC, formed during the first year of CASL operations (2010), is to facilitate interaction between CASL and eventual industry users of CASL technology and products. IC members can, for example, identify opportunities for access to experimental data, technical information, or initial testing. Members include fuel vendors, design engineering companies, engineering service providers, computing technology companies, and owners/operators of nuclear plants.

The CASL IC was formalized with a documented charter, or term of reference, that is updated annually. The charter was originally developed in 2010 but it was significantly modified in 2014 to align with plans that were established for the second five years of CASL operations (2015-2019). The charter specifies, e.g., scope for the IC, membership, management, meetings and expenses. The charter specifies that council members are expected to provide their time and travel at no cost to CASL except in circumstances where a member is in a key role and needs some limited reimbursement to be able to participate in council activities. Council meeting information (agendas, minutes, actions, supplementary reference material) is provided to the public on the CASL website (http://www.casl.gov).

While CASL is careful to ensure that all information discussed and disseminated outside CASL IC meetings and discussions is open, public information, CASL IC members are nevertheless required to sign a CASL "Master Non-Disclosure Agreement" (NDA) to ensure information exchanged related to the CASL program activities (including, but not limited to, R&D objectives, plans, and management plans) is protected appropriately. This information includes specific background information, which is considered by a CASL partner to be proprietary information or business sensitive, privileged, commercial, and/or financial information; information generated from discussions and/or exchanges between or among partners pursuant to this NDA is identified as business sensitive, or proprietary at the time of disclosure, orally or visually, and documented and confirmed as such.

Current IC membership (companies) includes:

- Nuclear fuel vendor and/or NSSS vendor: TVA, Duke, Dominion, EDF, Exelon
- Owner/operator of nuclear plants: WEC, NuScale, B&W Power Generation, GNF, AREVA
- Engineering design, service providers, and/or R&D: EPRI, Battelle, BMPC, Rolls Royce, Studsvik Scandpower
- Independent software vendors: ANSYS, CD-adapco, Dassault Systems, GSE Systems
- Computer technology: Cray, IBM, NVIDIA
- Ex-Officio: DOE NE, CASL BOD

Technical Execution: The CASL founding industrial partners (Westinghouse, EPRI, and TVA) are deeply involved in technical development of the CASL software. For example, the consortium's industry partners have supplied several "challenge problem integrators" who guide the CASL code development teams during creation of the consortium's models and software. The challenge problems that the integrators lead are associated with complex physical processes such as Chalk River Unidentified Deposits (CRUD) induced power shifts, CRUD induced localized corrosion and departure from nucleate boiling that cause operational and safety issues in light water reactors. Creation of integrated modeling and simulation software that addresses the challenge problems is at the heart of the CASL code development strategy.

The challenge problem integrators are tasked with developing charters and implementation plans that lay out technical strategies for achieving progress on each of the challenge problems, and the integrators work closely with the code development teams to guide development of codes that meet the implementation plan objectives. Meetings between the integrators and the code development teams are typically held at least once per month. The integrators also participate in weekly CASL management meetings that are held to discuss near term actions and information requests, they participate in monthly CASL collocation meetings where the entire CASL team comes together for a week to coordinate code development planning and implementation, they participate in the annual DOE reviews of CASL operations, and they contribute to reviews of CASL milestone reports that detail technical accomplishments and are held on an as needed basis. The integrators also work with their home organization management teams to identify and access experimental data that can be released to CASL for use in code validation. This data is extremely valuable to CASL because it allows the codes to be tested to ensure they produce results that match reality with an acceptable level of uncertainty.

CASL technical work is identified, deconstructed, planned, and executed using a milestone based approach. These milestones are recorded and communicated to all elements of the CASL team via a 6-month Plan of Record (PoRs). CASL documents each PoR allowing managed change such that the plan is dynamic and responsive to approved change while still meeting, or exceeding, commitments made at the onset of the PoR. Each PoR document is considered a documented implementation plan of Level

One (L1), Level Two (L2), and Level Three (L3) milestones, tasks, and risks for that six-month horizon. All milestone information (owner, scope, plan, completion criteria, etc.) is entered into the CASL milestone project management system (Trac - http://trac.edgewall.org/), which is CASL's project management document of record for quality purposes.

CASL implements a *virtual one-roof* to allow engagement of its researchers without the requirement for permanent physical relocation. The Virtual Office, Community, and Computing (VOCC) allows for physical collocation at CASL's main office at ORNL, while providing a virtual presence for close multidisciplinary collaboration and face-to-face meetings. The VOCC (www.voccnet.org) delivers a unified collaboration platform and creative work environment to support CASL's mission by bringing staff together under one virtual roof and to successfully operate a state-of-the-art scientific collaboration space (the VOCC Laboratory) that supports all CASL R&D use cases.

Collocation is defined as a significant collection of CASL participants coming together in one physical location for the purpose of executing CASL scope. This definition does not dictate the geographical site of the single physical location, but it requires that the site be a single physical setting with CASL staff gathered to conduct technical work. Often this physical location will be on the ORNL campus at the anchor CASL facility, but any setting where a significant collection of CASL staff gather in one physical location is considered to be collocation. CASL currently conducts one formal week of collocation every month, with the manner in which collocation is conducted alternating each month between physical and virtual. "Collocation week" is special relative to other normal working CASL weeks in that regular information-exchange weekly meetings and huddle sessions are replaced by deep dive reviews, planning sessions, and working meetings targeting specific technical activities associated with key milestone deliverables.

Setting the annual ~100+ CASL milestones is intrinsically intertwined with the resource allocation process, as discussed previously. Once L1 milestones are defined, supporting L2 milestones are defined jointly with appropriate risks and mitigation strategies along with focus area (FA) budget targets required to meet those L2 milestones in support of the L1 milestones and with knowledge of the risks. Third, scope, schedule, budget, and L3 milestones are set for every project, along with the personnel needed to achieve those milestones. Finally, the senior leadership analyzes the ability of proposed collective FA plans (milestone schedules/scope) to meet the defined L1 milestones and retain appropriate interdependency and linkages.

CASL tracks milestones delivery throughout the PoR. Recurring project team meetings and programmatic meetings, and meetings with DOE NE ensure risks other issues are quickly identified and addressed. Quality review of work delivered occurs throughout this phase and in closeout. Monthly program status updates are produced and sent to leadership covering recent activities, milestones (delivered, due near-term, and late), and issues. Change control is necessary as unplanned/ unforeseen/ non-managed change can upset schedules, costs, and resource allocation. CASL's change control process for milestones, is managed via a formal BCC (Baseline Change Control) process which defines and constrains the type, occurrence and potential impact a given change request may be have. All requests submitted are not necessarily approved.

The CASL industrial partners have also been instrumental during the planning and execution of "test stand" projects that have allowed the CASL codes to be tested by users who are not directly involved in code development. Test stands involve releasing a portion of the CASL codes to an independent host organization that can use the codes to analyze one or more technical problems that are of interest to CASL and the host. The host organization uses the codes, with only limited support from CASL, to complete analyses of the selected problems and then writes a report that describes the analyses and details any code issues or limitations that were identified during the testing. This process has proved invaluable to CASL because it supports early identification of issues that would limit the usefulness of the consortium's codes.

Three test stands were deployed to the CASL industrial partners during the first five years of CASL operations; the first was hosted by Westinghouse to predict startup neutronics response of the company's AP1000 reactors, the second was hosted by EPRI to compare CASL fuel performance modeling capabilities against EPRI's industry standard code, and the third was hosted by TVA to perform analysis of a lower plenum flow anomaly that has impacted a number of domestic nuclear reactors. In all three cases, CASL and the host organization learned important information about how to make the CASL tools user friendly, how the CASL tools can be incorporated into existing nuclear power analysis processes, and how the CASL team can provide support that encourages industrial use of VERA. The first test stand to be deployed outside of the CASL founding partnership is expected to be hosted by Areva and deployed during FY 2015. The CASL management team is planning to deploy at least one new test stand per year to other internal and external hosts during the remaining period of CASL operations.

Partnership Results: The principle product of CASL is VERA, which embodies the culmination of many of CASL's R&D activities and provides a tangible route to deploy CASL's technology to industry users. CASL integrated many infrastructure toolkits and created others to achieve the necessary unique virtual environment to support multiple physics applications (termed components). Any pre-existing physics components have been integrated to the Virtual Environment, modified as necessary for the commercial reactor application, and configured for coupling and/or interface with the other physics components, as needed. VERA provides a versatile environment with coupled combinations and varying fidelity levels adaptable to available computational resources. VERA incorporates the required solvers, coupling technologies, and uncertainty quantification (UQ) methodologies to consider feedback effects from multiple simultaneous physics and allows for a common input to run the many applications within the environment. The tools are designed for implementation on both today's leadership-class and on industry-class computing clusters.

The strategic vision for CASL is to evolve VERA into a standard modeling and simulation package used by industry to analyze nuclear reactor operations. To achieve this vision, CASL will continue supporting technology transfer of VERA through additional test stand deployments, initiation of an advanced modeling and simulation working group that encourages VERA users to share experiences and work together to support further development of the software, and continuing broad releases of the software tools to the nuclear energy user community.

Overall, CASL has generated tangible products during its first year of operation in 2010:

- Measurable progress and delivery of technical milestones (541 to date) and the commensurate ability of CASL software to model a wide range of nuclear reactor phenomena;
- Substantial scientific productivity, measured in part by high-quality, peer-reviewed publications, technical reports, and invited presentations (over 1,300 and counting); and
- Early and aggressive deployment of modeling and simulation technology to the nuclear energy community including limited releases of the CASL software tools through the Radiation Safety Information Computational Center (RSICC) and deployment of test stands at Westinghouse for AP1000 startup analysis, at EPRI for fuel performance analysis, and at TVA for computational fluid dynamics-based analyses of flows in the reactor's lower plenum.

Intellectual Property: One of CASL's primary goals is to rapidly and successfully transfer nuclear reactor simulation and modeling technologies to the U.S. nuclear industry, but the goal has to be tempered by the need to protect the consortium's and the United States' intellectual property. In order to ensure that CASL information is handled appropriately, a CASL Intellectual Property Management Plan (IPMP) has been developed, implemented, and is updated annually or as appropriate. The principal goals of the IPMP include: rapidly and successfully transferring new and previously developed nuclear reactor simulation and modeling technologies to the U.S. nuclear industry in order to facilitate the operational performance and longevity of today's operating reactors and the design and analysis of next-generation reactors and fuel technologies; openly disseminating scientific reports and results for public benefit; broadly and rapidly disseminating information among the CASL Members to maximize productivity and progress; and following the guiding principles for DOE technology transfer with regard to intellectual property, licensing and export control.

In creating the CASL IP, the CASL partners may use, incorporate, or modify software and inventions, which are created with funds other than CASL funding. As documented in CASL's IPMP, such software and inventions may be called out by the CASL partners as Background Intellectual Property **(**BIP). To the extent any CASL partner shares its BIP with any other CASL partners, such BIP shall be identified as such by the sharing CASL partner along with any specified restrictions. CASL IP may include BIP. CASL partners owning BIP will require separate license agreements with non-CASL partners for their BIP. Surveys of all relevant BIP that is being made available to CASL have been conducted with all partners. This list of BIP, included as part of the CASL IPMP, is periodically reviewed and updated to keep current.

CASL (Consortium) IP is any IP which is conceived and/or first actually reduced to practice, made, or generated in performance of the CASL Program with CASL Funding, including Subject Inventions as defined in 37 CFR 401, patent applications, issued patents, copyrights, rights in any technical data, computer software, trademarks or mask works, which are first made or generated in performance of the CASL Program. Any CASL partner that receives CASL funding can create CASL IP. All CASL partners receiving CASL funding may elect to retain title to inventions and may assert copyright in any copyrighted works. Each CASL partner is to report its CASL inventions to DOE Patent Counsel in accordance with the agreement under which it receives CASL funding. Each CASL partner must also disclose all CASL Inventions, copyrightable software, and tangible research products resulting from CASL funding. Each CASL partner must also disclose any executed fee and/or royalty-bearing licenses of CASL IP or BIP sought by CASL partners or third parties (or both) outside of the CASL Program.

All Derivative Works rights are specified in the CASL IPMP, depending upon whether it is derived from CASL IP or BIP. Separate license agreements may be negotiated for commercial rights in those Derivative Works. This includes the use of Derivative Works for providing a service to third parties who are not CASL Members as well as the creation of binary and/or executable codes created from CASL IP and Background IP for commercial purposes. Rights to distribute any derivative works created from CASL IP and/or BIP will be in accordance with any restrictions on BIP that may impact future release of CASL IP or use of VERA (e.g., open source license requirements and/or proprietary license requirements).

Several classes of licenses are currently in use or under development to support distribution of CASL technology. These license classes include a government use license, a test and evaluation (T&E) license, a noncommercial license, and a commercial license. The T&E license is used for the test stands while the commercial license that is under development will be used for profit-based businesses. The non-commercial license that is also under development will allow the use of CASL software for research and development, education, and other nonprofit purposes. Both the commercial and non-commercial licenses will be made available during the second five years of CASL operations. The commercial license, as currently scoped, will not allow redistribution (for sale or otherwise) of the technology (i.e., VERA) outside of the licensee's organization; this allowance, if appropriate and approved by DOE, will occur in a separate product license.

To the maximum extent possible, ORNL (on behalf of CASL) will serve as the single point of contact for licensing, subject to DOE approval and to conditions established by owners of software contained in the CASL tools. The objective of this strategy is to minimize the number of organizations that users of the CASL tools will have to negotiate with in order to establish licenses that will be required to use VERA. An inter-institutional agreement (IIA) between the four organizations that have primary ownership of the CASL software tools (ORNL, INL, LANL, UM) is under development to establish sublicensing terms and conditions.

Performance Metrics: Four strategic goals were identified during development of the original CASL proposal to focus CASL on completion of its mission. These goals have not been modified since CASL began operations.

- Develop and effectively apply modern virtual reactor technology;
- Address light water reactor design, operational and safety challenges;
- Engage the nuclear energy community through modeling and simulation;
- Deploy new partnership and collaboration paradigms.

The CASL metrics have been divided into a group of outcome metrics that are tied to strategic performance, and a group of operating metrics that evaluate short-term project performance. Quantitative measures that are used to evaluate whether or not CASL performance with respect to each measure exceeds expectations, meets expectations, or is below expectations have been identified for each of the metrics.

Metrics have been developed by the CASL management team to help ensure CASL is making progress toward achieving these strategic goals. The metrics have been updated two times since CASL began operations in July 2010. The first update was made during FY 2012 and reflected a shift in CASL priorities away from startup operations and toward code development. The second update was made at the beginning of FY 2015 and reflects a shift in priority away from pure code development and toward code deployment.

Metric performance is typically reviewed every six months to coincide with the CASL planning cycle. Data is generally collected by subject matter experts and recorded in a spreadsheet maintained by the CASL project manager. The review results are generally shared with the program's extended leadership team to support discussion of necessary corrective actions, and the results and corrective action plans are then summarized for presentation to the CASL Board of Directors. Board input is collected and incorporated into response planning, and the metric results are presented to DOE as part of the CASL annual review.

Current measures of CASL performance and outcome metrics are documented in DOE annual review presentations, Management Plans, six-month Plan-of-Record (PoR) documents. These results are not typically published outside of DOE or the CASL partners, although they could easily be made available to the public if requested.

CASL Enduring Value: The strategic vision for CASL sees its M&S technology evolving into the *nuclear enterprise community model* for nuclear reactor and power plant M&S technology. Early adoption and technology transfer to the nuclear energy community in the form of Test Stands, a post-CASL entity, M&S working group, and broad release of VERA will demonstrate industry acceptance, integration and adaption. Broad engagement of the nuclear community allows CASL to build interest, trust, confidence, and acceptance.

In a second phase, CASL will expand its funded industry partnership (beyond its founding industry partnership) to include other nuclear fuel and design vendors and utilities as a required step in expanding the range of applicability of its M&S technology. CASL will also continue its Education Program and expand its reach to universities outside of the CASL partnership. CASL will continue to seek guidance from its Science and Industry Councils. CASL's engagement goal goes beyond building acceptance of CASL-developed M&S capabilities, but strives to build an appreciation for the benefits to be derived from the use of and reliance upon predictive M&S capabilities. Sustainability of CASL-developed technologies will be assured through a proactive plan to establish a stable and long-lived post-CASL entity—an innovation center for nuclear energy M&S and a vibrant M&S working group—to assume and carry on CASL's technology by bringing together and engaging leading experts from academia, federal agencies, and industry.

Lessons Learned: There are many lessons learned in executing a complex DOE program like CASL; these lessons translate into a collection of programmatic strategies, implementations, and activities that would be undertaken differently or more efficiently within the context of a new program with similar constraints (e.g., public-private partnership, translational R&D, five-year term, etc.). Most of these lessons learned surfaced during the first 18 months of CASL (startup) but some did not manifest themselves until later (steady state operations). These are itemized briefly below (in random order).

- If the lead institution retains all funding authority for its partnering institutions (as in CASL), the efficient and timely execution of subcontracts for all partnering organizations is paramount. This is especially important in incremental funding scenarios such as the U.S. Government's budget cycle, which often results in Continuing Resolution acts typified by monthly funding installments. Here a team of contracting authorities, procurement officials, and technical contract monitors must be available to address and execute contract modifications on a regular (monthly) basis.
- Formulate, document, and implement formal baseline change control (BCC) policies and procedures for any required change (scope, schedule, budget) of the baseline program plan. A BCC serves many useful purposes, but most importantly a BCC forces communication of risks (e.g., schedule slip or scope reduction) among the stakeholders before they become realized problems and a BCC ensures an open, formal process for movement of funds across work breakdown structure (WBS) elements.
- Formulate, document and implement a Technology Control Plan (TCP) that articulates procedures for the processing, storage, and transmissions of sensitive data (export controlled, proprietary, etc.) among partner organizations and staff. All staff must understand the TCP protocols (thru required training) to ensure that risks for loss of sensitive data are as low as possible.
- Actively track performance through formal reviews of staff- and team-delivered milestones and annual reviews of partner organizations.
- Balance the tension between development of capabilities and the development and application of products by having appointed Product Integrators for driving critical applications, products, and outcomes that crosscut capability elements within the Hub.
- Actively pursue if and where capabilities developed elsewhere (e.g., in other federal programs, universities, etc.) can be leveraged as opposed to recreation.

- Impose project management processes (planning, execution, tracking, review) early in the lifetime of the Hub so that staff become quickly used to the constraints associated with working within a large integrated program. Expect and manage the widely-differing institutional views of the levels of project management required for successful execution.
- Aggressively embrace secure virtual collaboration technologies and solutions to ameliorate expensive and time-consuming travel required for physical collocation. Physical collocation is essential for success, but not always required for the task at hand.
- Formulating and tracking quantitative performance metrics is very difficult; drive the process of metrics definition and collection early and often, otherwise others external to the Hub will "provide the answer". Devise performance metrics for regularly monitoring the "vital signs" of the Hub and outcome metrics that are directly tied to strategic goals. Utilize councils, committees, and boards to regularly and objectively assess the science, technology, and management performance of the Hub.
- Aggressively pursue formulating, documenting, and formalizing partner organization agreements for managing and sharing proprietary and intellectual property (IP) data. These agreements must include clauses for background IP, licensing of IP, inventions and patents, and the creation and distribution of derivative works.
- Implement provisions and milestones for deployment of developed technology, even if the technology is in a beta state. This early deployment (or "test stand") of technology gives invaluable feedback, while the technology is still under development, from prospective users and customers on whether the technology is "useable and useful". This early feedback can influence the subsequent technology development activities and plans.
- Do not underestimate the importance of required institutional infrastructure supporting the R&D activities. Directly support the infrastructure, or, more optimally, leverage existing institutional infrastructure through aggressive in-kind and cost-share contributions as well as integrating with the stakeholder federal programs that are stewards of the infrastructure.
- Take great care to ensure that the end use requirements driving the R&D activities for the product technology are properly understood. Do not tacitly assume that the appropriate requirements always call for a fundamental and detailed understanding of all phenomena – use existing products and technologies as a "baseline" for relative comparisons. Where possible devise "progression problems" for explicit measurement of if and how these requirements are being met.
- Maintain an open resource allocation and adjustment process that empowers the technical leadership team to make budget decisions based on requirements- and priority-based R&D needs. Understand and appreciate resource allocation expectations of partner organizations but do not commit to explicit levels; rely instead on the R&D needs for recommended allocations.
- Do not underestimate the importance of coordinated, clear, concise, and regular outreach and communication. Embrace all forms of communication (internet, social media, quarterly tech notes, brochures, one-pagers, etc.) and target a wide audience. Maintain a concerted effort to make available all scientific publications (include internal technical reports, milestones, presentations) of relevance. Track if and how the external community is digesting this material.

Recommendations for Future Hubs: A detailed account of CASL procedures found to be effective can be found in the CASL Management Plan, Program Plan, and Renewal Application. The key procedures recommended for reuse are highlighted here.

- Have clear deliverables that solve industry issues and are driven by a well-defined yet dynamic plan. Commit to a hierarchical milestone plan with tangible deliverables and define products integrated across capabilities.
- Impose a strategy of delivering prototype products early and often. Early deployment of the Hub's technology into an industrial environment for rapid and enhanced testing, use, and ultimate adoption to support real-world applications is crucial for ultimate adoption and commercialization.
- Define customers and users, with "industry pull" ensured by an industry council that is chartered and engaged for early, continuous, and frequent interface and engagement of end-users and technology providers. Use the industry council for critical review of plans and products, which helps to drive the product from becoming the Hub's product to the industry's product.
- Implement a true private-public partnership with parity where possible in management, leadership, and execution. Engage industry broadly (in the case of nuclear energy: vendors, owners/operators, R&D) and at all levels of execution. Involving the best and brightest technical personnel is crucial for success and credibility, using virtual collaboration technologies for daily interactions.
- Plan and execute with a minimum five-year horizon for completion and funding, acknowledging that a renewal option for a second five years may be useful and appropriate. A five-year period ensures the ability to attract and retain community leaders yet, upon execution, forces specific paths and decisions.
- Empower the Hub to be led by one institution with resource allocation authority and responsibility. This empowerment, while not a guarantee of success, enables risk-informed agility through assignment of clear authority and responsibility.
- Enable the lead Hub institution and Hub senior leadership to make annual scope, schedule, and within-Hub resource allocation decisions as long as execution and performance warrants (e.g., annual DOE Hub reviews are positive).
- Formulate and charter a Board of Directors (BOD) to provide regular (3-4 times annually) oversight and advice on management, plan, and science and technology strategy. The BOD is not a useful body unless the Hub senior leadership knows how to effectively utilize its assets.
- Formulate and charter independent councils to review and advise on quality and relevance of science and technology. Utilize the Science Council for independent assessment of whether the scientific work planned and executed is of high quality and supports attaining the Hub's goals. This should motivate Hub senior leadership to more directly address problems with timely and needed decisions.